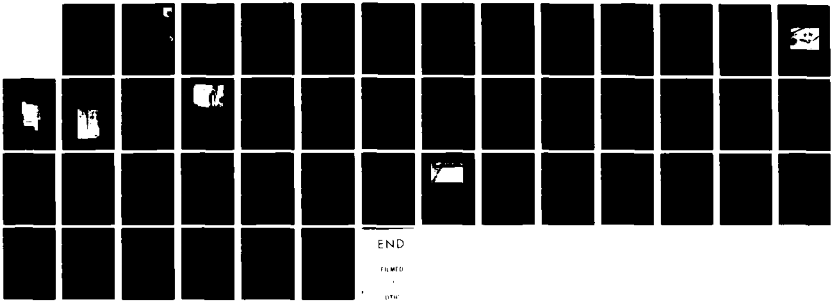
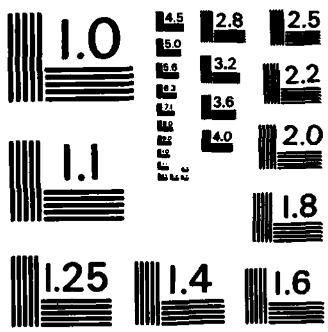
AD-A121 029 REPETITIVE SWITCHING FOR INDUCTIVE ENERGY STORAGE(U) 1/1
IAP RESEARCH INC DAYTON OH J P BARBER ET AL. AUG 82
IAP-TR-82-2 AFWAL-TR-82-2088 F33615-81-C-2024
UNCLASSIFIED F/G 9/1 NL






MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AD A121029

12

AFWAL-TR-82-2088

# REPETITIVE SWITCHING FOR INDUCTIVE ENERGY STORAGE

DTIC
ELECTE
NOV 3 1982
S D
H

JOHN P. BARBER
THOMAS J. TRZASKA

IAP RESEARCH, INC.
7546 MCEWEN ROAD
DAYTON, OHIO 45459

AUGUST 1982

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AFB, OHIO 45433

82 11 03 004

DTIC FILE COPY

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

## REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

| | | |
|---|---|---|
| 1. REPORT NUMBER<br>AFWAL-TR-82-2088 | 2. GOVT ACCESSION NO.<br>AD-A121029 | 3. RECIPIENT'S CATALOG NUMBER<br>00684 |
| 4. TITLE (and Subtitle)<br>REPETITIVE SWITCHING FOR INDUCTIVE ENERGY STORAGE | | 5. TYPE OF REPORT & PERIOD COVERED<br>Final Technical Report<br>April 1981 - June 1982 |
| | | 6. PERFORMING ORG. REPORT NUMBER<br>IAP-TR-82-2 |
| 7. AUTHOR(s)<br>John P. Barber<br>Thomas J. Trzaska | | 8. CONTRACT OR GRANT NUMBER(s)<br>F33615-81-C-2024 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>IAP Research, Inc.<br>7546 McEwen Road<br>Dayton, Ohio 45459 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS<br>62203F<br>3145 3260 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>Aero Propulsion Laboratory (AFWAL/POOS)<br>AF Wright Aeronautical Laboratories<br>Wright-Patterson Air Force Base, OH 45433 | | 12. REPORT DATE<br>August 1982 |
| | | 13. NUMBER OF PAGES<br>40 |
| 14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) | | 15. SECURITY CLASS. (of this report)<br>Unclassified |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Switch-Repetitive
Opening Switch
High Current
Switch-Mechanical

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the development and testing of a high current repetitive switch. The objective was to develop a switch capable of repetitively diverting current and energy from an inductive energy store into a load. A mechanical switch employing sliding electrical contacts was built and tested. The switch demonstrated performance exceeding design goals. In an inductive energy storage circuit the switch successfully commutated a current of 7640 A at a repetition rate of 33 Hz. The switch has

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) been operated at repetition rates ranging from 1 Hz to 49 Hz. Over 1600 successful commutations have been achieved with no failures.

ADDENDUM

AFWAL-TR-82-2088

In between recent switch tests another attempt was made to use a current shunt in series with the 5 MW Ling power supply used in the switch tests. This attempt was completely successful and provided an improved calibration for the Ragowski coils used in all of the previous current measurements. As a result of the improved calibration all references to current values throughout this report should be multiplied by a factor of 1.13 to agree with the improved calibration.

Accession For
NTIS GRA&I ☑
DTIC TAB ☐
Unannounced ☐
Justification
By
Distribution/
Availability Codes
Dist | Avail and/or Special
A

## TABLE OF CONTENTS

## LIST OF ILLUSTRATIONS

## LIST OF TABLES

# SECTION 1

# INTRODUCTION

## 1.1 BACKGROUND

Over the past decade, the Air Force has developed considerable interest in the use of inductors to store electrical energy. Recently, the Air Force funded studies of advanced space propulsion and weapons concepts which are ideally suited to the use of inductive energy storage systems. One of the critical technologies required in the development of inductive energy storage systems is a repetitive switch capable of diverting current and energy from the inductor to the load. Current levels up to a few hundred thousand amperes, peak voltages of a few kilovolts and pulse repetition rates up to a few tens of hertz are typically required. No switch designs or components are available to meet these requirements.

The technical problems of switching in an inductive energy storage circuit can be traced to one or more of four performance requirements. In most applications, the duty cycle of the switch is very high and the switch must carry high current almost continuously. The switch must have very low resistance in the "on" state to limit energy dissipation. The second performance requirement involves commutation of the current to the load. The switch must rapidly achieve voltage sufficient to commutate current into the load. During commutation, the switch must dissipate additional energy. The third requirement of switch performance is standoff voltage. The switch must develop adequate voltage standoff capability to withstand rapidly changing load voltage. Finally the switch must operate repetitively, switching at frequencies up to a few tens of hertz.

Existing switching technologies such as solid state devices, gas discharge devices, and conventional circuit breakers cannot accommodate these severe operating conditions. Therefore, in order for inductive energy storage systems to be applied, new switching technology must be developed.

## 1.2 SCOPE AND PURPOSE

The purpose of this program was to design, fabricate and deliver to the Air Force a repetitively operated high current switch suitable for use in an inductive energy storage circuit. The design goals of the program were to switch 8.5 kA at a repetition rate of 50 Hz with a 90% duty cycle and 50 m/s opening speed. The mechanical integrity and switching capabilities of the switch were to be demonstrated.

We provided the United States Air Force with a high current repetitive switch which meets or exceeds program requirements. The design and construction of the switch make it an excellent test bed for further scientific and engineering study of repetitive high current switching. This program is an important step in addressing the technological gap which today limits the application of inductive energy storage technology.

## SECTION 2

## DESIGN

### 2.1 THE CONCEPT

We chose as the basis of our design an electromechanical switch concept which utilizes massive current conductors and sliding electrical contacts. The approach provides the combination of low loss in the "on" state, and high switch opening speed which are desired in an inductive energy storage application.[1]

This approach to switching was demonstrated in the "rail switch" devices used in the Australian National University (ANU) rail gun[2] and in the EMACK facility.[3] These switches operate in a linear fashion for a single shot mode. Our goal was to preserve the key features of the "rail switch" device while using a rotating current conductor to provide a repetitive operating mode.

The design goal was to build a switch to demonstrate the concept illustrated in Figure 1. A metal disk or drum with an insulating slot is rotated past a pair of current collecting contacts. When the insulating insert passes under one or both of the current collecting contacts, current interruption will begin. The motion of the separating contacts is transverse (as opposed to normal in a conventional circuit breaker) and the opening

---

[1]Barber, J. P., "Pulse Switching of Superconducting Inductive Energy Stores," IAP-TM-79-001, Sep. 1979.

[2]Barber, J. P., "The Acceleration of Macroparticles in a Hypervelocity Electromagnetic Accelerator," Ph.D. Thesis, The Australian National University, 1972.

[3]McNab, I. R., Deis, D. W., et al, "DC Electromagnetic Launcher Development: Phase I," 79-9B2-EMACK-R7, November 16, 1979.

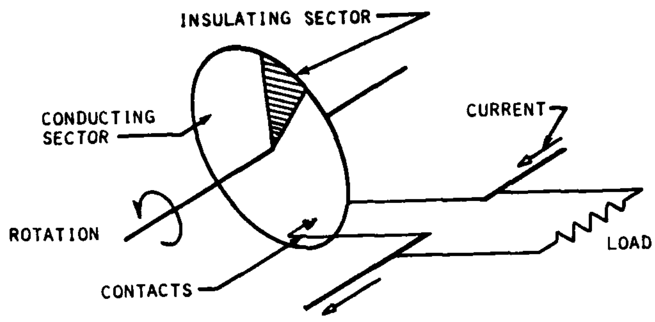



Figure 1. Rotating Switch Concept.

speed can be very high. Current capacity can be increased by increasing current collection area and number of contacts. This switching concept is electrically identical to the single shot switch used on the Australian National University rail gun.[2] The switch would, therefore, be capable of direct current commutation into a rail gun at frequencies of interest (1 to 100 Hz).

Throughout the design process much effort was spent to ensure that components were simple to fabricate and maintain. Many design decisions were made to utilize components or techniques which have been proven in other fields of research. Three areas where proven technology was used are current collection, brush actuation and rotor drive. Similar current collection and brush actuator systems have been used for over a decade in high current homopolar generators. The variable speed rotor drive which was chosen is a commercially available industrial device designed for service much more severe than that anticipated here. Our goal was to produce a rugged, flexible piece of equipment at minimum cost.

## 2.2 THE DESIGN

### 2.2.1 The Rotor

The rotor was a simple copper disk with a pie shaped insulating wedge as illustrated in Figure 2. The disk was mounted on a vertical shaft with heavy aluminum hubs. The rotor was carefully balanced and could be operated at 3400 RPM with extremely low vibration levels.

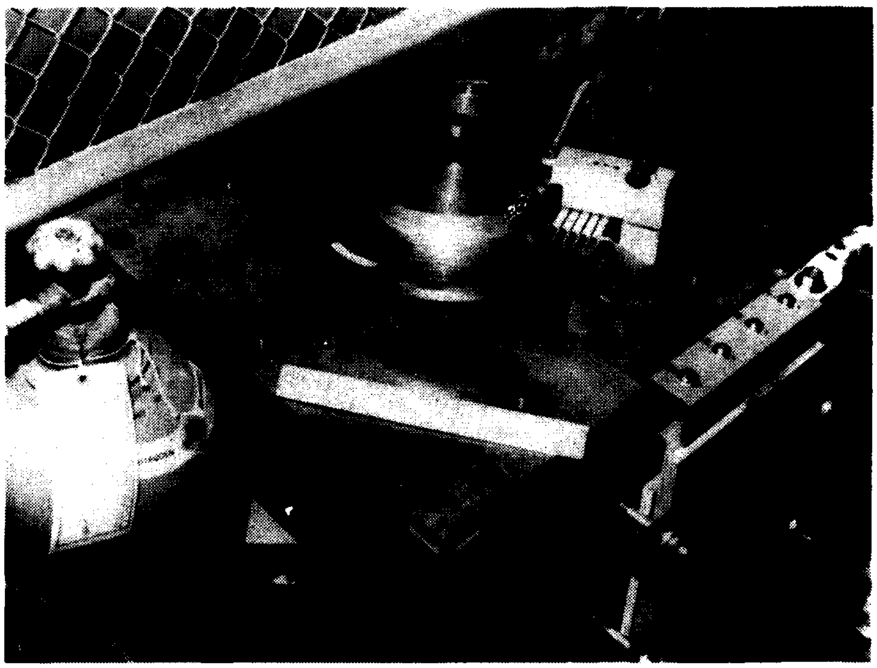


Figure 2. The Switch Rotor, Brushes, Brush Actuators and Load Resistor in Place

The insulating insert was epoxy resin cast in place in recesses approximately 0.5 mm deep machined into both faces of the rotor. Several types of epoxy resins were investigated. Epoxies, unfortunately, do not bond well to copper and the final selection of Hysol R9-2039 resin was based on its' compatability with copper.

2.2.2 Current Collectors

The installed current collectors together with actuators are shown in Figure 2. A view of the disassembled brushes is shown in Figure 3. The brushes were 1 cm cubes of CM1S copper graphite and were torch soldered to copper straps using a 95/5, Sn/Sb solder. The straps acted both as the mechanical mounting device and the current shunts for the brushes. Brushes were mounted on both the top and bottom of the rotor.

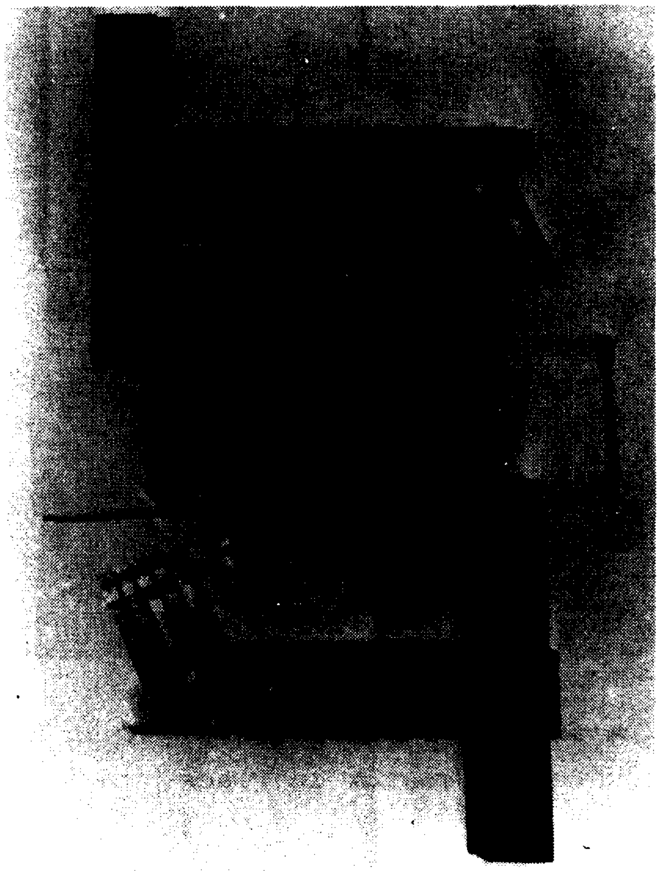


Figure 3. The Brushes and Brush Mounting Hardware.

Brush actuation was achieved with a simple pneumatic device which permitted separate independent actuation of each brush. Actuation pressures were chosen to produce adequate contact force and maintain a low voltage drop between the brush and rotor. The brush mounting straps provided the return force when actuation pressure was removed. The actuators are shown installed in Figure 2.

### 2.2.3 The Drive System

The rotor drive system was based on a 10 HP AC motor with a variable speed drive. The motor was mounted vertically in a welded steel frame and direct coupled to the rotor via a torque transducer. The drive motor, torque transducer and couplings are illustrated in Figure 4. The motor and variable speed drive are capable of operation at any speed between 0 and 4000 RPM.

Figure 4. The Motor and Drive Train Assembly Installed.

### 2.2.4 The Load Resistor

The load resistor was constructed from thin stainless steel plates arranged in a "folded" geometry to provide high resistance and low inductance. The resistor is shown connected to the switch terminals in Figure 2. The load resistor was designed such that plates could be added to vary the resistance from a minimum of 1.4 mΩ to a maximum of approximately 14 mΩ.

### 2.2.5 Safety Enclosures

High speed rotating machinery presents a number of serious hazards. These hazards are described in detail in Appendix A. The complete switch with all safety enclosures installed is shown in Figure 5. (This photograph also shows the inductor partially connected to the switch.) The rotor housing consists of a circular steel enclosure designed to contain any fragments which might be generated during brush or rotor failures. The top of this enclosure is a double thickness polycarbonate plate to permit visual access while providing sufficient fragment perforation resistance. The motor, shafts and couplings are all enclosed by steel panels bolted to the switch frame. Physical access to the shafts is completely prevented when these panels are in place.

## 2.3 THE TEST CIRCUIT

The test circuit for the rotary switch was designed to simulate, as closely as possible, the switching requirements of an electric rail gun. The primary limitation of the test circuit derives from the power supply, a 5 MW, 3 phase rectifier, with a maximum output current rating of 12,000 A. (During this program less than 8,000 A was actually available.) This current is at least an order of magnitude lower than electric rail gun requirements. The low current and limited scope of the program

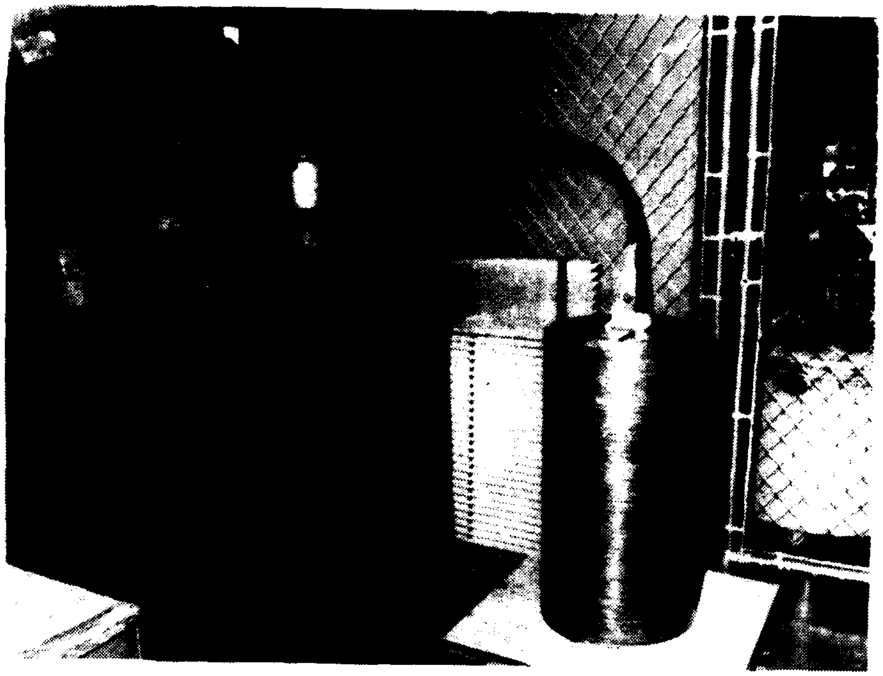


Figure 5. The Complete Switch With Safety Enclosures Installed, Partially Connected to the Energy Storage Inductor.

also precluded switching into a "real" rail gun load. A low inductance resistive test load was designed to simulate initial rail gun loads. (The time dependence of rail gun impedence is difficult to simulate and beyond the scope of this program.) The test circuit is illustrated in Figure 6.

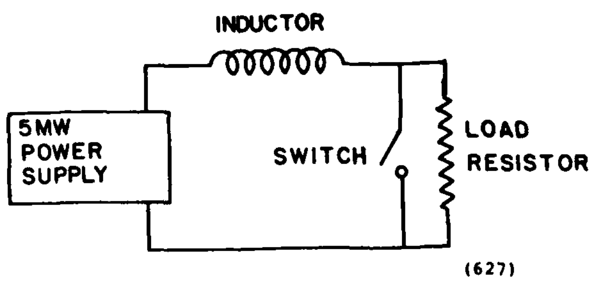



Figure 6. The Test Circuit.

The test circuit consists of the 5 MW power supply connected in series with an energy storage coil and the switch. The test load is connected in parallel with the switch. The power supply drives current through the inductor and normally closed switch. When the switch opens, current is commutated into the load. The voltage across the load (and switch) immediately rises and energy is extracted from the coil. When the switch closes the power supply recharges the inductor. The operation of the circuit is identical to that required for a repetitive electric rail gun.[5]

The coil was designed and fabricated under separate programs. It is a simple single layer solenoid 0.4 m in diameter and 0.8 m long. It has 56 turns of 1.27 cm square copper bar. The computed inductance is 500 μH and the resistance is 7.85 mΩ. The computed time constant is 64 ms and it stores 18 kJ at the design current of 8,500 A.

---

[5]Barber, John P., McCormick, Timothy J., Bauer, David P., "Electromagnetic Gun Study," AFATL-TR-81-82, Eglin AFB, FL, September 1981.

# SECTION 3

# RESULTS

The switch was installed and operated at the Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio. The switch operated successfully over a wide range of current and switching frequency. As of this writing it has produced over 1600 commutations without a failure and without any measurable performance degradation. In this section, we describe the operational characteristics of the switch first. Then we review the results of the current switching tests.

## 3.1 OPERATIONAL CHARACTERISTICS

During the acceptance testing of the switch, an extensive investigation of the electrical and mechanical characteristics of the switch was conducted. The performance of the switch met or exceeded operational design goals.

### 3.1.1 Rotor Speed Tests and Speed Calibration

The switch was tested for mechanical integrity by operating it at 3400 rpm for five minutes. This test exceeded the test specification of operating at design speed (3000 rpm) plus 10% for 5 minutes. The switch was operated at 3400 rpm for a combined total of well over 15 minutes. There was no indication of weakness or impending failure in any rotor or drive component at any speed tested. No cracks were observed in visual post test inspections. Vibration and noise levels were extremely low at all speeds. No strong resonances were detected.

Figure 7 shows the calibration curve for the motor speed control. The motor controller and rotor are capable of reaching speeds of up to 4000 rpm; however, the switch should not be operated above the proof test speed of 3400 rpm with the present rotor configuration.

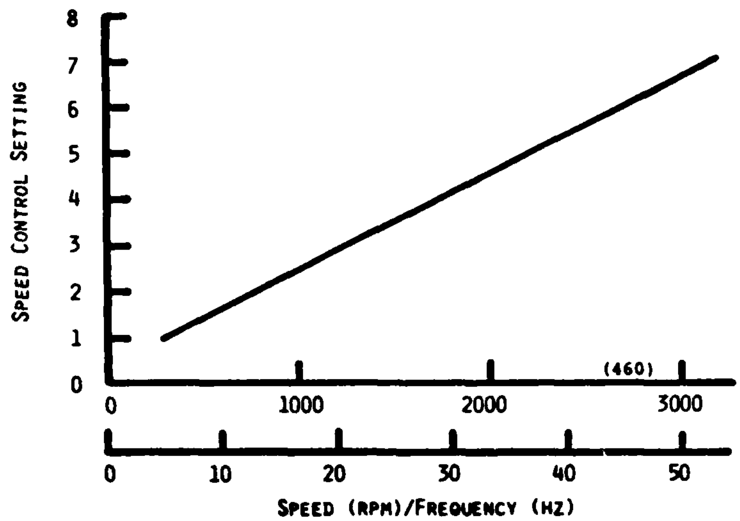



Figure 7. Control Setting Versus Switch Speed

### 3.1.2 Voltage Breakdown Tests

Large voltage transients can be generated in the switch when high currents are interrupted. The voltage breakdown and grounding of system components were therefore tested. The system is designed such that the motor, torque transducer and frame of the switch are electrically tied to system ground. The drive shaft and rotor of the switch are electrically isolated from the frame and motor. Each ground connection was checked and verified during installation.

Voltage breakdown between the switch rotor and the frame was tested. A proof test voltage of 2000 V was applied between the switching circuit (the rotor with brushes applied and the current collection bus bars) and the frame. No breakdown was observed although this voltage exceeded the design voltage (1000 V) by a factor of two.

### 3.1.3 Torque Transducer Calibration

The torque transducer was calibrated using a 56 N-m capacity beam type torque wrench. The ouput of the transducer was conditioned with a NATEK A.C. strain gauge bridge, filtered through a low pass filter, and recorded on a Honeywell Visicorder oscillograph. Figure 8 shows the output voltage versus torque for this system.

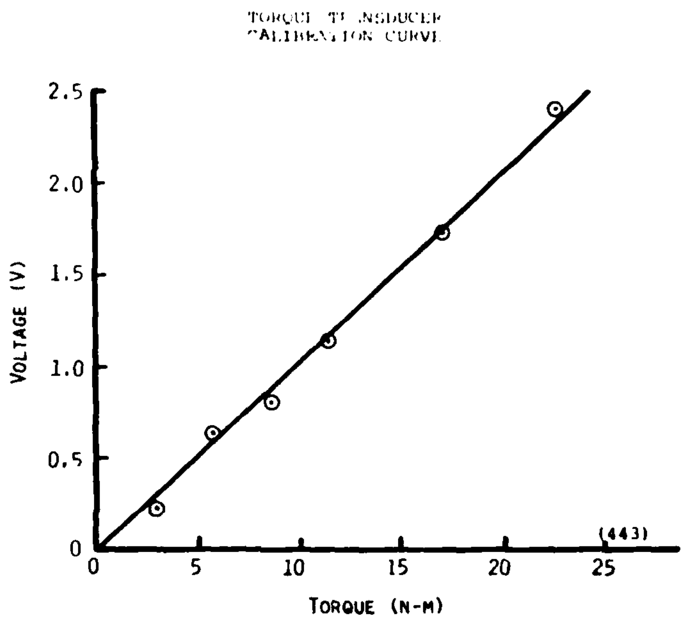



Figure 8. Torque Transducer Calibration Curve.

### 3.1.4 Brush Actuator Calibration

The brush actuation system was calibrated by placing a small load cell underneath a single brush actuator. Air pressure was applied to the actuator and the resultant force measured. The actuation force was measured with and without the brushes in place. The actuation force was measured for various brush displacements in order to investigate the effects of brush wear on contact force.

Figure 9 shows actuation pressure versus contact force for a typical actuator. The actuation force decreases with brush displacement for constant actuation pressure. This is due to the force developed by elastic deflection of the brush straps. The measured value of actuator force is slightly lower than the theoretical value arrived at by multiplying actuator area by the pressure. This is most probably due to calibration errors in the pressure regulator which was used to set the actuation pressure.

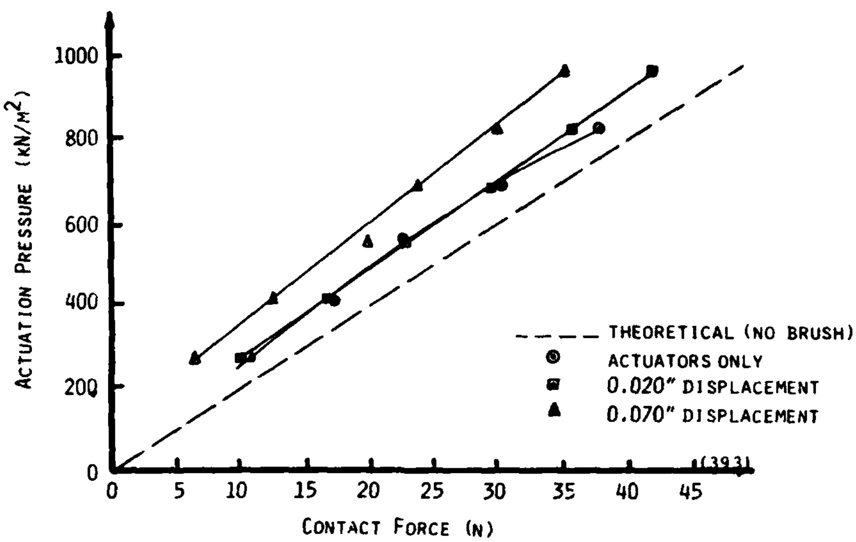



Figure 9. Actuation Pressure Versus Contact Force.

### 3.1.5 Operating Power Requirements

Figure 10 shows the measured drive power versus rotor speed at various brush actuation pressures. For the condition of no current, maximum actuation pressure and maximum rotor speed, the switch consumed approximately 6200 W (8.3 HP) well within the 7400 W (10 HP) available.

Approximately 1.96 N-m of torque are required to overcome bearing friction and windage losses in the system. This torque appears to be independent of rotor

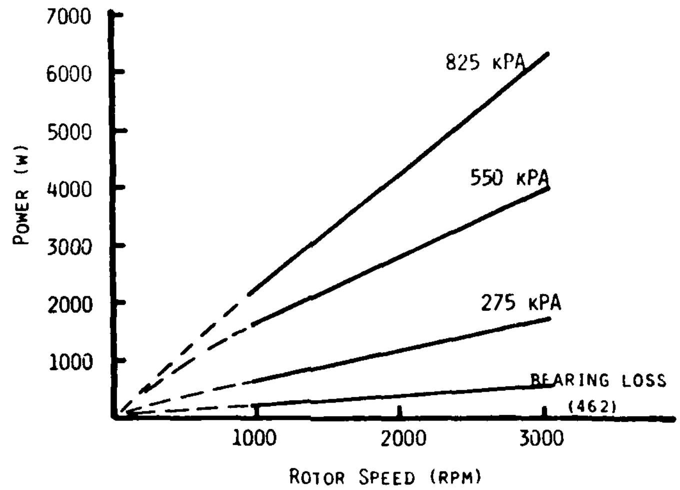



Figure 10. Drive Power Versus Rotor Speed.

speed. A power loss of approximately 650 W (0.9 HP) results at full rotor speed.

### 3.1.6 Brush Friction/Wear

Figure 11 shows brush friction coefficient versus actuation pressure for two rotor speeds (under 'no current' conditions). The data indicates that brush friction coefficient is a function of both actuation pressure and sliding speed. The friction coefficient between the brush and the rotor decreases with increasing speed and increases with increasing actuation force. Friction coefficient decreased when current was applied to the brushes. These observations are consistant with the known mechanisms governing sliding friction.

The friction coefficient value observed here is somewhat higher than that reported by Marshall[4] and

---

[4]Marshall, R. A., "Sliding Brushes for the Canberra Homopolar Generator," The Australian National University, EP-RR 27, May 1973.

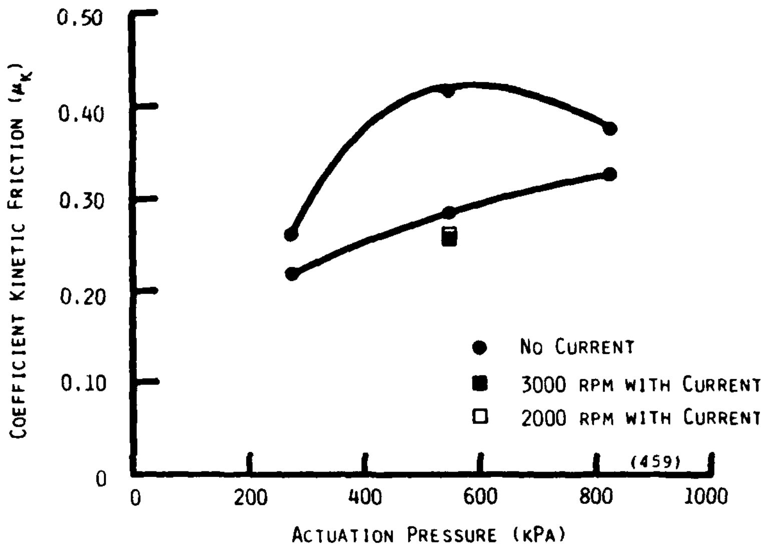



Figure 11. Brush Friction Coefficient Versus Actuation Pressure.

the brush material supplier, Morganite. Morganite quotes a coefficient of friction of 0.1, while Marshall has reported a value of 0.2 to be typical. We believe that the higher values which we observe are due mostly to insufficient wear-in time on the brushes. Typically, friction decreases as brushes "wear-in" to the slip rings. The higher than expected friction force poses no problems for switch operation and is not of immediate concern.

During the design phase of this program, brush wear was a concern. In the testing thus far, brush wear has not been significant. After 1500 commutations, brush wear has been so slight that the brushes have not fully seated on the rotor.

## 3.2 CURRENT COMMUTATION TESTS

A series of current commutation or switching tests were conducted to demonstrate the capabilities of the switch. These tests were conducted at the Air Force Aero Propulsion Laboratory at Wright-Patterson AFB, Ohio using a 5 MW high current power supply. Problems with the control system in the power supply limited the maximum current available to approximately 7600 A.

A matrix of tests was conducted in an attempt to establish the switching limits of the device. Current, switch frequency, brush actuation force, and load impedance were independently varied. Table 1 is a chronological summary of the conditions of each test conducted. A total of 1631 successful commutation or switching events were observed. The switch never failed to commutate the total current into the load over the entire range of test conditons.

Table 1

TEST CONDITIONS

| TEST NUMBER | PEAK CURRENT (A) | SWITCHING FREQUENCY (HZ) | NUMBER OF COMMUTATIONS | COMMENTS |
|---|---|---|---|---|
| 1 | 0.00 | 0.00 | 0 | POWER SUPPLY MALFUNCTION, NO POWER SUPPLIED TO COIL |
| 2 | 1,630.00 | 33.30 | 33 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 3 | 2,050.00 | 32.30 | 29 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 4 | 2,890.00 | 32.80 | 60 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 5 | 3,240.00 | 32.70 | 74 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 6 | 4,050.00 | 32.80 | 79 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 7 | 4,020.00 | 48.70 | 93 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 8 | 370.00 | 32.50 | 7 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 9 | 2,640.00 | 32.80 | 115 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 10 | 0.00 | 16.30 | 3 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE, RECORDER PAPER RAN OUT |
| 11 | 3,530.00 | 16.50 | 27 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 12 | 3,610.00 | 8.40 | 21 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 13 | 5,360.00 | 33.60 | 77 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 14 | 5,460.00 | 33.60 | 95 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 15 | 6,170.00 | 0.00 | 14 | BRUSHES NOT ACTUATED, CONSIDERABLE SPARKING, HIGH LOAD CURRENT |
| 16 | 6,170.00 | 32.30 | 76 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 17 | 7,310.00 | 32.90 | 55 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 18 | 0.00 | 0.00 | 0 | POWER SUPPLY MALFUNCTION, RECORDER PAPER RAN OUT |
| 19 | 3,960.00 | 32.80 | 61 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 20 | 3,880.00 | 32.80 | 65 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 21 | 3,940.00 | 32.80 | 91 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE, SOME SPARKING |
| 22 | 5,580.00 | 32.70 | 65 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE, SPARKING, SOME SLOT DAMAGE |
| 23 | 5,500.00 | 32.30 | 71 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE, SPARKING, SOME SLOT DAMAGE |
| 24 | 5,590.00 | 32.50 | 62 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE, SPARKING |
| 25 | 6,750.00 | 32.50 | 72 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE, LOW SPARKING |
| 26 | 3,150.00 | 31.60 | 20 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE, MINIMAL SPARKING |
| 27 | 2,270.00 | 31.90 | 12 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE, MINIMAL SPARKING |
| 28 | 5,170.00 | 31.90 | 31 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE, MINIMAL SPARKING |
| 29 | 6,720.00 | 31.80 | 49 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE, MINIMAL SPARKING |
| 30 | 5,5[illegible].00 | 32.50 | 67 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE, SOME SPARKING |
| 31 | 7,640.00 | 33.00 | 56 | SUCCESSFUL COMMUTATION, SPARKING, BLUE FLASH, POWER SUPPLY MALFUNCTION |
| 32 | 0.00 | 0.00 | 0 | ROTOR SPEED CALIBRATION, NO CURRENT |
| 33 | [illegible],050.00 | 12.50 | 11 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 34 | 1,9[illegible]0.00 | 10.40 | 18 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 35 | 2,020.00 | [illegible].53 | 12 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 36 | 1,970.00 | 4.17 | 4 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 37 | 2,100.00 | 3.14 | 4 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE |
| 38 | 1,970.00 | 0.93 | 2 | SUCCESSFUL COMMUTATION, LOW SWITCH VOLTAGE, ACTUATION PRESSURE REDUCED |
| | | | =============== | |
| | | | 1,631 | |

The highest current commutated was 7640 A on test 31. In this test the switch successfully commutated 56 pulses at 33 Hz into the load. The highest switching frequency tested was 48.7 Hz on test 7. The current switched was 4020 A and 93 commutations were achieved. The lowest frequency tested was 0.93 Hz on test 38. Two commutations of 1970 A were recorded.

A typical commutation record is illustrated in Figure 12. This data was taken from test 28. The test conditions were:

1) Set Current - 6000 A
2) Switching Frequency - 33.3 Hz
3) Load Resistance - 4.0 mΩ

The figure shows three consecutive commutations out of a total of 31 recorded on this test. The switch current, load current and load voltage are shown. The average switch current is 4410 A and there is considerable ripple. The peak current was 5170 A and occurred at the peak of the recurring "saw tooth" deviation. This "saw tooth" effect was caused by power supply malfunctions and occurred at all set currents above about 4000 A.

The primary characteristics of the commutation are illustrated in Figure 12. The switch is "on" and carries the current most of the time. When the insulating slot slides under the current collectors, the switch current rapidly falls to zero. At the same time current is commutated into the load and the load current rapidly rises from zero to the full circuit current. The load voltage closely follows load current indicating that the load behaves essentially as a resistor. There is no evidence in the voltage record of the formation of an arc or any other voltage excursions.

In the following paragraphs the test data are presented and discussed.

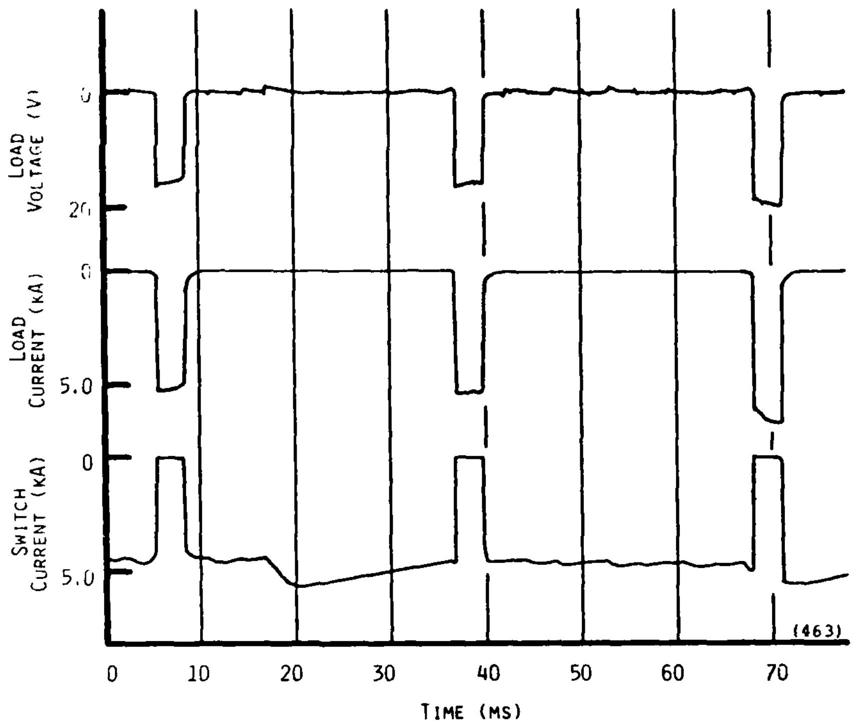



Figure 12. Typical Commutation Events.

### 3.2.1 *Power Supply Performance*

The power supply was operated in a current control mode. The desired test current was preset. An "on" switch was activated and the power supply then ramped up to the set current and held steady until a stop switch was set. Due primarily to recurrent control circuitry problems the power supply failed to reach set current at settings above 2000 A. In addition, above a set current of 4000 A, the supply developed considerable ripple largely in the form of "saw tooth" peak current excursions. The switch operated completely satisfactorily in spite of these problems. The current settings and measurements for all the tests is summarized in Table 2.

At the lowest current setting, 1000 A, the power supply delivered considerably more current than expected (1530 A to 1630 A). The ripple was relatively

Table 2

TEST CURRENT DATA

| CURRENT SETTING (A) | AVERAGE CURRENT (A) | PEAK CURRENT (A) | AVERAGE /SET RATIO | PEAK /SET RATIO | PEAK/ AVERAGE RATIO | TEST DURATION (SEC) | TEST NUMBER |
|---|---|---|---|---|---|---|---|
| 1000.00 | 1,530.00 | 1,630.00 | 1.530 | 1.630 | 1.065 | 0.991 | 2 |
| 2000.00 | 319.00 | 370.00 | 0.159 | 0.185 | 1.160 | 0.215 | 8 |
| 2000.00 | 1,810.00 | 1,970.00 | 0.905 | 0.985 | 1.088 | 2.151 | 38 |
| 2000.00 | 1,890.00 | 1,970.00 | 0.945 | 0.985 | 1.042 | 1.731 | 34 |
| 2000.00 | 1,890.00 | 2,020.00 | 0.945 | 1.010 | 1.069 | 1.594 | 35 |
| 2000.00 | 1,890.00 | 1,970.00 | 0.945 | 0.985 | 1.042 | 0.959 | 36 |
| 2000.00 | 1,890.00 | 2,100.00 | 0.945 | 1.050 | 1.111 | 1.274 | 37 |
| 2000.00 | 1,930.00 | 2,060.00 | 0.965 | 1.030 | 1.067 | 0.880 | 33 |
| 2000.00 | 2,020.00 | 2,050.00 | 1.010 | 1.025 | 1.015 | 0.898 | 3 |
| 3000.00 | 2,600.00 | 2,640.00 | 0.867 | 0.880 | 1.015 | 3.506 | 9 |
| 3000.00 | 2,860.00 | 2,890.00 | 0.953 | 0.963 | 1.010 | 1.829 | 4 |
| 3500.00 | 3,210.00 | 3,240.00 | 0.917 | 0.926 | 1.009 | 2.263 | 5 |
| 4000.00 | 3,020.00 | 3,150.00 | 0.755 | 0.787 | 1.043 | 0.633 | 26 |
| 4000.00 | 3,380.00 | 3,530.00 | 0.845 | 0.882 | 1.044 | 1.636 | 11 |
| 4000.00 | 3,610.00 | 3,610.00 | 0.902 | 0.902 | 1.000 | 2.500 | 12 |
| 4000.00 | 3,800.00 | 4,020.00 | 0.950 | 1.005 | 1.058 | 1.910 | 7 |
| 4000.00 | 3,800.00 | 3,880.00 | 0.950 | 0.970 | 1.021 | 1.982 | 20 |
| 4000.00 | 3,800.00 | 3,940.00 | 0.950 | 0.985 | 1.037 | 2.774 | 21 |
| 4000.00 | 3,860.00 | 4,050.00 | 0.965 | 1.012 | 1.049 | 2.409 | 6 |
| 4000.00 | 3,860.00 | 3,960.00 | 0.965 | 0.990 | 1.026 | 1.860 | 19 |
| 5000.00 | 4,280.00 | 5,360.00 | 0.856 | 1.072 | 1.252 | 2.292 | 13 |
| 6000.00 | 2,100.00 | 2,270.00 | 0.350 | 0.378 | 1.081 | 0.376 | 27 |
| 6000.00 | 4,410.00 | 5,170.00 | 0.735 | 0.862 | 1.172 | 0.972 | 28 |
| 6000.00 | 4,490.00 | 5,450.00 | 0.748 | 0.910 | 1.216 | 2.827 | 14 |
| 6000.00 | 4,6[illegible]0.00 | 5,500.00 | 0.770 | 0.917 | 1.190 | 2.198 | 23 |
| 6000.00 | 4,[illegible]0.00 | 5,590.00 | 0.770 | 0.932 | 1.210 | 2.062 | 30 |
| 6000.00 | 4,660.00 | 5,590.00 | 0.777 | 0.932 | 1.200 | 1.908 | 24 |
| 6000.00 | 4,670.00 | 5,580.00 | 0.778 | 0.930 | 1.195 | 1.988 | 22 |
| 7000.00 | 5,670.00 | 6,170.00 | 0.810 | 0.881 | 1.088 | | 15 |
| 7000.00 | 5,920.00 | 6,170.00 | 0.846 | 0.881 | 1.042 | 2.353 | 16 |
| 7500.00 | 6,220.00 | 6,760.00 | 0.829 | 0.901 | 1.087 | 2.215 | 25 |
| 7500.00 | 6,470.00 | 6,720.00 | 0.863 | 0.896 | 1.039 | 1.541 | 29 |
| 8000.00 | 6,930.00 | 7,310.00 | 0.866 | 0.914 | 1.055 | 1.672 | 17 |
| 8500.00 | 6,720.00 | 7,640.00 | 0.791 | 0.899 | 1.137 | 1.697 | 31 |

low at 6.5%. *Test 8 at a set current of* 2000 A shows a very low current primarily due to the short test duration (0.215 s) which did not allow adequate time for the power supply to ramp up to current. In general if the test duration was less than 1 s the power supply did not reach a stable maximum current (ex. tests 8, 26, and 27). The ripple (ratio of peak/average current) was worst at the intermediate current settings (5000 A and 6000 A). At lower current levels the "saw tooth" excursions disappeared while at the highest current the magnitude of these excursions remained constant as the average current increased. The longest test duration was 3.5 s on test 9. Most tests had a total duration of about 2 s.

The highest set current for which data was obtained was 8500 A. The peak delivered current at this setting was 7640 A. At settings above 8500 A, the power supply failed, fuses were blown and no current was delivered to the switch.

### 3.2.2 Switch Timing Data

The motor controller was preset for each test using the speed calibration curve shown in Figure 7 to provide a desired switching frequency. From the data records for each test we measured the actual switching frequency, the pulse width of the commutated current, the duty cycle (ratio of switch "on" time to total cycle time) and the opening speed of the contacts. This data is summarized in Table 3.

The set speed was varied from 60 rpm (1 Hz) to 3000 rpm (50 Hz) and the actual measured switching frequency varied from 0.93 Hz to 48.7 Hz. The pulse width is a linear function of the rotational period of the rotor (≅10%) and varies, as expected, from 110 ms to 2 ms over the range of frequencies tested.

The duty cycle (ratio of switch "on" time to switch cycle time) was expected to be 0.90 or slightly larger (due to the finite width of the current collectors). The test data shows that the average duty cycle over all the tests was 0.9044. There does not appear to be a significant variation of duty cycle with switching frequency.

The opening speed of the switch contacts is an important factor in achieving current commutation and developing stand-off voltage capability. The switch was designed to operate down to approximately 20 m/s opening speed. It was tested down to 0.89 m/s opening speed and continued to commutate satisfactorily. The maximum opening speed tested was 46.63 m/s, very close to the design maximum of 50 m/s.

### 3.2.3 Load Pulse Data

The functional purpose of the switch is to

Table 3

SWITCH TIMING DATA

| SET SPEED (RPM) | SWITCHING FREQUENCY (Hz) | PULSE WIDTH (SEC) | DUTY CYCLE | OPENING SPEED (M/S) | TEST NUMBER |
|---|---|---|---|---|---|
| 60.00 | 0.93 | 0.110000 | 0.8977 | 0.89 | 38 |
| 180.00 | 3.14 | 0.033000 | 0.8964 | 3.01 | 37 |
| 240.00 | 4.17 | 0.023000 | 0.9041 | 3.99 | 36 |
| 450.00 | 7.53 | 0.013000 | 0.9021 | 7.21 | 35 |
| 600.00 | 8.40 | 0.011000 | 0.9076 | 8.04 | 12 |
| 600.00 | 10.40 | 0.009300 | 0.9033 | 9.96 | 34 |
| | AAAAAAAAAAAA | AAAAAAAAAAAA | AAAAAAAAAAAA | AAAAAAAAAAAA | |
| 600.00 | 9.40 | 0.010150 | 0.9054 | 9.00 | |
| 750.00 | 12.50 | 0.007800 | 0.9025 | 11.97 | 33 |
| 1000.00 | 16.30 | 0.005500 | 0.9103 | 15.61 | 10 |
| 1000.00 | 16.50 | 0.005800 | 0.9043 | 15.80 | 11 |
| | AAAAAAAAAAAA | AAAAAAAAAAAA | AAAAAAAAAAAA | AAAAAAAAAAAA | |
| 1000.00 | 16.40 | 0.005650 | 0.9073 | 15.70 | |
| 2000.00 | 33.30 | 0.003000 | 0.9001 | 31.89 | 2 |
| 2000.00 | 32.30 | 0.003000 | 0.9031 | 30.93 | 3 |
| 2000.00 | 32.80 | 0.003000 | 0.9016 | 31.41 | 4 |
| 2000.00 | 32.70 | 0.003000 | 0.9019 | 31.31 | 5 |
| 2000.00 | 32.80 | 0.003000 | 0.9016 | 31.41 | 6 |
| 2000.00 | 32.50 | 0.003500 | 0.8862 | 31.12 | 8 |
| 2000.00 | 32.80 | 0.003000 | 0.9016 | 31.41 | 9 |
| 2000.00 | 33.60 | 0.002600 | 0.9126 | 32.17 | 13 |
| 2000.00 | 33.60 | 0.002800 | 0.9059 | 32.17 | 14 |
| 2000.00 | 32.30 | 0.003000 | 0.9031 | 30.93 | 16 |
| 2000.00 | 32.90 | 0.002600 | 0.9145 | 31.50 | 17 |
| 2000.00 | 32.80 | 0.002900 | 0.9049 | 31.41 | 19 |
| 2000.00 | 32.80 | 0.002800 | 0.9082 | 31.41 | 20 |
| 2000.00 | 32.80 | 0.002900 | 0.9049 | 31.41 | 21 |
| 2000.00 | 32.70 | 0.003000 | 0.9019 | 31.31 | 22 |
| 2000.00 | 32.30 | 0.002800 | 0.9096 | 30.93 | 23 |
| 2000.00 | 32.50 | 0.002800 | 0.9090 | 31.12 | 24 |
| 2000.00 | 32.50 | 0.002800 | 0.9090 | 31.12 | 25 |
| 2000.00 | 31.60 | 0.002900 | 0.9084 | 30.26 | 26 |
| 2000.00 | 31.90 | 0.002900 | 0.9075 | 30.55 | 27 |
| 2000.00 | 31.90 | 0.002900 | 0.9075 | 30.55 | 28 |
| 2000.00 | 31.80 | 0.002800 | 0.9110 | 30.45 | 29 |
| 2000.00 | 32.50 | 0.002800 | 0.9090 | 31.12 | 30 |
| 2000.00 | 33.00 | 0.003200 | 0.8944 | 31.60 | 31 |
| | AAAAAAAAAAAA | AAAAAAAAAAAA | AAAAAAAAAAAA | AAAAAAAAAAAA | |
| 2000.00 | 32.61 | 0.002917 | 0.9049 | 31.23 | |
| 3000.00 | 48.70 | 0.002000 | 0.9026 | 46.63 | 7 |
| | AAAAAAAAAAAA | AAAAAAAAAAAA | AAAAAAAAAAAA | AAAAAAAAAAAA | |
| | 26.80 | 0.008541 | 0.9044 | 25.66 | |

Copy available to DTIC does not permit fully legible reproduction

transfer energy from an inductive energy store into a load. The test load for these tests was a low inductance resistor. The resistance could be varied by adding plates to the resistor. Two configurations were employed: a low resistance configuration containing two resistor plates with a nominal resistance of 1.4 mΩ; and a high resistance configuration with 6 plates and a nominal resistance of 3.6 mΩ. On each test we measured the load current, the load voltage, the pulse duration and the total number of pulses. From these measurements we calculated the apparent load resistance, the energy transferred to the load in each pulse and the total energy transferred during the test. This data is summarized in Table 4.

Table 4

LOAD PULSE DATA

| NUMBER OF RESISTOR PLATES | PEAK CURRENT (A) | PEAK VOLTAGE (V) | LOAD RESISTANCE (OHMS) | SWITCH FREQUENCY (HZ) | PULSE DURATION (SEC) | PULSE ENERGY (J) | TOTAL ENERGY (J) | TEST NUMBER |
|---|---|---|---|---|---|---|---|---|
| 2 | 1630.00 | 2.00 | 0.001227 | 33.30 | 0.003000 | 9.18 | 201.96 | 2 |
| 2 | 2050.00 | 3.60 | 0.001756 | 32.30 | 0.003000 | 21.82 | 421.78 | 3 |
| 2 | 370.00 | 0.80 | 0.002162 | 32.50 | 0.003500 | 0.61 | 2.87 | 8 |
| 2 | 2060.00 | 3.70 | 0.001796 | 12.50 | 0.007800 | 49.68 | 364.31 | 33 |
| 2 | 1970.00 | 3.50 | 0.001777 | 10.40 | 0.009300 | 54.49 | 653.86 | 34 |
| 2 | 2020.00 | 3.50 | 0.001733 | 7.53 | 0.013000 | 73.21 | 559.68 | 35 |
| 2 | 1970.00 | 3.50 | 0.001777 | 4.17 | 0.023000 | 134.76 | [illegible] | 36 |
| 2 | 2100.00 | 3.70 | 0.001762 | 3.14 | 0.033000 | 180.87 | 482.33 | 37 |
| 2 | 1970.00 | 3.30 | 0.001675 | 0.93 | 0.110000 | 577.39 | [illegible] | 39 |
| 2 | 2640.00 | 3.90 | 0.001477 | 32.80 | 0.003000 | 29.64 | 2,272.40 | 9 |
| 2 | 2890.00 | 4.20 | 0.001453 | 32.80 | 0.003000 | 36.04 | 1,441.44 | 4 |
| 2 | 3240.00 | 4.90 | 0.001512 | 32.70 | 0.003000 | 45.26 | 2,232.88 | 5 |
| 2 | 4020.00 | 6.00 | 0.001493 | 48.70 | 0.002000 | 41.80 | [illegible],591.60 | 7 |
| 2 | 4050.00 | 6.00 | 0.001481 | 32.80 | 0.003000 | 64.85 | 3,415.33 | 6 |
| 2 | 3530.00 | 4.90 | 0.001388 | 16.50 | 0.005800 | 92.14 | 1,658.50 | 11 |
| 2 | 3610.00 | 5.00 | 0.001385 | 8.40 | 0.011000 | 198.55 | 2,779.70 | 12 |
| 2 | 5360.00 | 7.40 | 0.001381 | 33.60 | 0.002600 | 63.43 | 3,256.05 | 13 |
| 2 | 5460.00 | 7.70 | 0.001410 | 33.60 | 0.002800 | 77.95 | 4,936.61 | 14 |
| 2 | 6170.00 | 8.50 | 0.001378 | 32.30 | 0.003000 | 145.63 | 7,378.69 | 16 |
| 2 | 7310.00 | 9.90 | 0.001354 | 32.90 | 0.002600 | 167.57 | 6,144.14 | 17 |
| | | | AAAAAAAAAAAAA | | | | | |
| 2 | | | 0.001569 | | | | | |
| 6 | 3880.00 | 15.50 | 0.003995 | 32.80 | 0.002800 | 164.92 | 7,146.53 | 20 |
| 6 | 3150.00 | 13.60 | 0.004317 | 31.60 | 0.002900 | 115.61 | 1,541.41 | 26 |
| 6 | 3940.00 | 15.70 | 0.003985 | 32.80 | 0.002900 | 166.40 | 10,095.05 | 21 |
| 6 | 3960.00 | 16.00 | 0.004040 | 32.80 | 0.002900 | 170.15 | 6,919.38 | 19 |
| 6 | 5500.00 | 20.10 | 0.003655 | 32.30 | 0.002800 | 235.44 | 11,143.93 | 23 |
| 6 | 5590.00 | 21.80 | 0.003900 | 32.50 | 0.002800 | 245.78 | 10,978.35 | 30 |
| 6 | 5590.00 | 22.00 | 0.003936 | 32.50 | 0.002800 | 245.30 | 10,139.17 | 24 |
| 6 | 2270.00 | 11.00 | 0.004846 | 31.90 | 0.002900 | 60.90 | 487.20 | 27 |
| 6 | 5170.00 | 20.00 | 0.003868 | 31.90 | 0.002900 | 217.41 | 4,493.20 | 28 |
| 6 | 5580.00 | 21.60 | 0.003871 | 32.70 | 0.003000 | 253.58 | 10,988.51 | 22 |
| 6 | 6720.00 | 25.60 | 0.003810 | 31.80 | 0.002800 | 413.04 | 12,492.80 | 29 |
| 6 | 6760.00 | 25.60 | 0.003787 | 32.50 | 0.002800 | 417.98 | 20,063.23 | 25 |
| 6 | 7640.00 | 29.80 | 0.003901 | 33.00 | 0.003200 | 580.61 | 21,676.03 | 31 |
| | | | AAAAAAAAAAAAA | | | | | |
| 6 | | | 0.003993 | | | | | |

The apparent load resistance, as determined from current and voltage measurements, is very close to the expected value. The two plate configuration had an average resistance of 1.57 mΩ, only slightly higher than the calculated value of 1.4 mΩ. This is most probably due to heating of the load. The six plate configuration has an apparent resistance of 3.99 mΩ which is also slightly higher than the calculated 3.6 mΩ.

Copy available to DTIC does not permit fully legible reproduction

The energy per pulse transferred to the load varied from less than 1 J for the lowest current test on the two plate resistor to 580 J for the highest current test on the six plate resistor. The total energy transferred during one complete test varied from a few joules up to over 21 kJ.

### 3.2.4 Contact Behavior

The behavior of the brush/slip ring contacts was investigated during the tests. The performance of the contacts is critical to scaling the switch to higher current levels. The contact voltage drop and current density (current/brush) were measured on each shot. In addition, the surface or sliding speed was also computed. The results for all shots for which data was obtained are summarized in Table 5.

Table 5

CONTACT DATA SUMMARY

| CURRENT DENSITY (A/BRUSH) | ACTUATION FORCE (N) | SURFACE SPEED (M/S) | CONTACT VOLTAGE (V) | TEST NUMBER |
|---|---|---|---|---|
| 63.80 | 226.85 | 31.12 | 0.01 | 8 |
| 306.00 | 226.85 | 31.89 | 0.01 | 2 |
| 362.00 | 35.58 | 0.89 | 0.45 | 38 |
| 378.00 | 165.58 | 3.01 | 0.25 | 37 |
| 378.00 | 165.58 | 3.99 | 0.20 | 36 |
| 378.00 | 165.58 | 7.21 | 0.25 | 35 |
| 378.00 | 165.58 | 9.96 | 0.25 | 34 |
| 386.00 | 165.58 | 11.97 | 0.25 | 33 |
| 404.00 | 226.85 | 30.93 | 0.01 | 3 |
| 520.00 | 226.85 | 31.41 | 0.22 | 9 |
| 572.00 | 226.85 | 31.41 | 0.20 | 4 |
| 642.00 | 226.85 | 31.[illegible] | 0.20 | 5 |
| 676.00 | 226.85 | 15.80 | 0.30 | 11 |
| 700.00 | 173.47 | 30.55 | 0.20 | 27 |
| 722.00 | 226.85 | 8.04 | 0.30 | 12 |
| 760.00 | 226.85 | 31.41 | 0.35 | 21 |
| 760.00 | 226.85 | 31.41 | 0.45 | 20 |
| 760.00 | 226.85 | 46.63 | 0.57 | 7 |
| 772.00 | 226.85 | 31.41 | 0.30 | 6 |
| 772.00 | 226.85 | 31.41 | 0.40 | 19 |
| 856.00 | 226.85 | 32.12 | 0.45 | 13 |
| 898.00 | 226.85 | 32.12 | 0.47 | 14 |
| 924.00 | 289.12 | 30.93 | 0.40 | 23 |
| 924.00 | 289.12 | 31.12 | 0.55 | 10 |
| 932.00 | 289.12 | 31.12 | 0.40 | 24 |
| 934.00 | 226.85 | 31.31 | 0.50 | 22 |
| 1,006.70 | 173.47 | 30.26 | 0.60 | 26 |
| 1,184.00 | 226.85 | 30.93 | 0.47 | 16 |
| 1,244.00 | 289.12 | 31.12 | 0.70 | 25 |
| 1,344.00 | 289.12 | 31.60 | 0.60 | 31 |
| 1,386.00 | 226.85 | 31.50 | 0.57 | 17 |
| 1,470.00 | 173.47 | 30.55 | 0.60 | 28 |
| 2,156.70 | 173.47 | 30.45 | 0.80 | 29 |

The current density varied from 64 A/brush up to 2157 A/brush. The maximum current density tested was 28% above the design value of 1700 A/brush. This implies that the switch has a current carrying capacity of at least 10,875 A.

The contact voltage drop remained low over the entire range of current density tested. The results are shown in Figure 13. Actuator force and surface speed did not appear to have a significant effect on contact voltage drop. The dashed curve in Figure 13 is data taken by Marshall.[4] A large error band on our data is due to the low resolution of our voltage measurement.

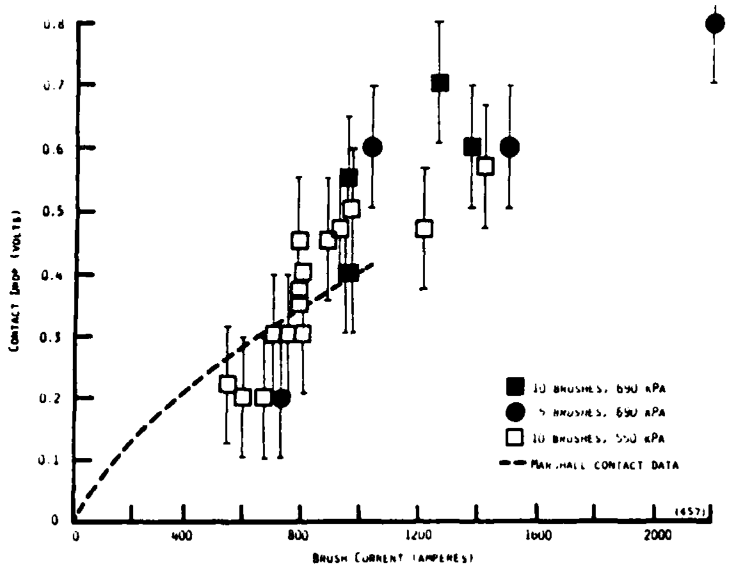



Figure 13. Contact Drop Versus Current Per Brush.

During the current tests we measured the torque due to brush friction and the results are summarized in Table 6. The average coefficient measured was 0.26. The data does not show any significant dependence on surface speed (over the range covered by the data), on actuation force or on current density. The data base is, however,

Table 6

FRICTION DATA

| SURFACE SPEED (M/S) | ACTUATION FORCE (N) | CURRENT DENSITY (A/BRUSH) | FRICTION COEFFICIENT | TEST NUMBER |
|---|---|---|---|---|
| 30.93 | 226.85 | 404.00 | 0.2516 | 3 |
| 30.93 | 226.85 | 1,184.00 | 0.2614 | 16 |
| 31.31 | 226.85 | 642.00 | 0.2725 | 5 |
| 31.41 | 226.85 | 572.00 | 0.2725 | 4 |
| 31.41 | 226.85 | 772.00 | 0.2781 | 6 |
| 31.50 | 226.85 | 1,386.00 | 0.2386 | 17 |
| 31.89 | 226.85 | 306.00 | 0.2670 | 2 |
| 46.63 | 226.85 | 760.00 | 0.2572 | 7 |
| | | | AAAAAAAAAAAA | |
| | | | 0.2624 | |

very limited and these observations should be treated with caution.

### 3.2.5 Rotor Damage

Surface damage of the rotor, insulator and brushes was of concern. During current switching tests, current carrying components of the switch were carefully inspected before and after each test to monitor damage.

In the tests conducted damage to rotor, insulator and brushes was very slight. Most of the damage occurred in the copper slip ring at the edge between the copper and the insulating sector. Figure 14 shows a photograph of the rotor taken after test 26. This photograph shows some minor discoloration at the copper-insulator edge and some pitting of the copper.

The damage on the insulator surface occurred during early mechanical tests and was traced to brush failure. The cause of the brush failure was isolated and corrected and there was no further damage.

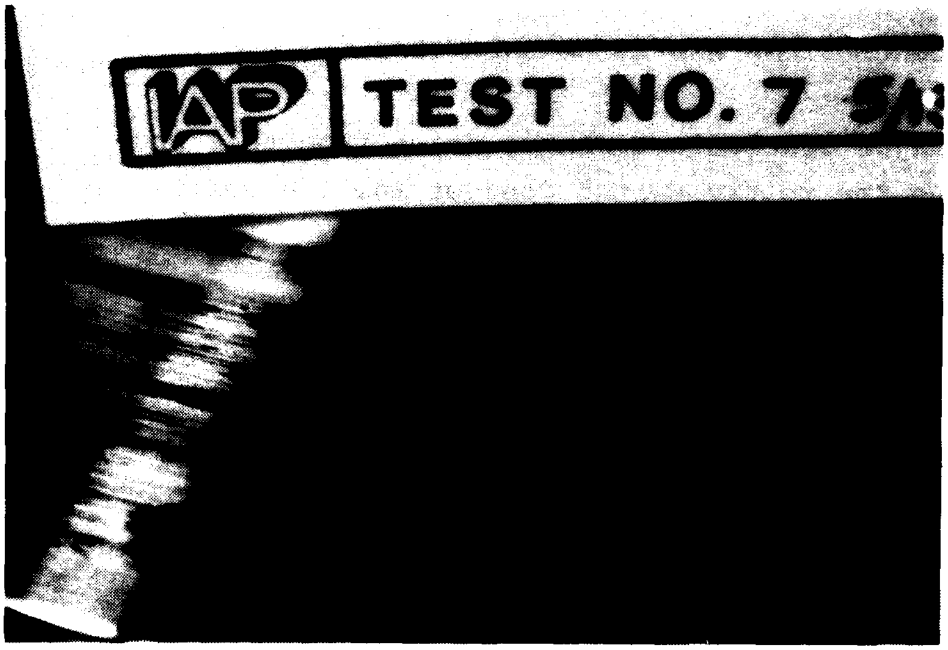



Figure 14. Photograph of Slip Ring Damage.

# SECTION 4

## CONCLUSIONS AND RECOMMENDATIONS

Several major conclusions can be drawn from this program concerning the rotary switch concept and the demonstration hardware tested.

The rotary high current switching concept works. In testing to date, the switch has successfully commutated current over 1600 times without a single failure. Damage to the current collectors, slip ring and insulator have been minimal. The switch met all of the design requirements and performance goals.

The limits of performance of the demonstration hardware have not been reached. The switch performed completely satisfactorily operating at extremes of current and speed. There are no observations thus far which indicate that this switch concept cannot be scaled to higher current.

This switch demonstrated commutation voltages, pulse durations, switching frequencies and burst durations extending well beyond the ranges of interest for electric rail guns.[5] The technical feasibility of the concept has been demonstrated. There remain, however, important unanswered questions concerned primarily with switch sizing at the much higher current levels required for electric rail guns. The sizing estimates which have been done[5] were based on collector current densities and switch opening speeds which were demonstrated or exceeded in this program. An electric rail gun switch scaled directly from this device could obviously be designed, however, it would be relatively large and cumbersome. Significant reductions in switch size and mass can undoubtably be achieved with a better understanding of collector current density, collector geometry and opening speed limitations.

The demonstration hardware can be used to generate much more information. This test program was limited to verifying the performance goals of the switch. Much more information in the areas of current capability, switch speed limits, commutation voltage, and stand-off voltage could be generated.

We recommend that further testing be conducted with the demonstration switch to clarify the switching phenomena and establish better design limits. We also recommend that the design and testing of a higher current device be undertaken to extend the concept demonstration into current regimes of direct interest in EM launchers.

## REFERENCES


1. Barber, J. P., "Pulse Switching of Superconducting Inductive Energy Stores," IAP-TM-79-001, Sep. 1979.

2. Barber, J. P., "The Acceleration of Macroparticles in a Hypervelocity Electromagnetic Accelerator," Ph.D. Thesis, The Australian National University, 1972.

3. McNab, I. R., Deis, D. W., et al, "DC Electromagnetic Launcher Development: Phase I," 79-9B2-EMACK-R7, November 16, 1979.

4. Marshall, R. A., "Sliding Brushes for the Canberra Homopolar Generator," The Australian National University, EP-RR 27, May 1973.

5. Barber, John P., McCormick, Timothy J., Bauer, David P., "Electromagnetic Gun Study," AFATL-TR-81-82, Eglin AFB, FL, September 1981.

# APPENDIX A

## HIGH CURRENT ROTARY SWITCH
## PRELIMINARY HAZARD ANALYSIS

DR. JOHN P. BARBER
IAP RESEARCH, INC.

TABLE OF CONTENTS

# LIST OF TABLES

## SECTION 1

## INTRODUCTION

The purpose of this preliminary hazard analysis is to identify hazards which are inherent in the operation of the high current repetitive switch built under contract, F33615-81-C-2024, "Repetitive Switching for Inductive Energy Storage." We have identified the primary hazards, evaluated the severity and probability of occurance, and the actions required to reduce the severity and/or probability of occurance to satisfactory levels. Our analysis is based on the methods and guidelines outlined in MIL-STD-882A, 28 June 1977.

Hazard severity is ranked into four categories in MIL-STD-882A. Those categories are:

(1) Category 1 - Catastrophic - These hazards may cause death or complete system loss.

(2) Category 2 - Critical - These hazards may cause severe injury, severe occupational illness or major system damage.

(3) Category 3 - Marginal - These hazards may cause minor injury, minor occupational illness or minor system damage.

(4) Category 4 - Negligible - These hazards will not result in injury, occupational illness or system damage.

Frequency of occurance is divided into six categories ranging from physically impossible to frequent. The classifications are summarized in Table 1. Our approach to the design of the switch and the development of operational guidelines was to either reduce the hazard severity to category 3 or 4 or to reduce the probability of occurance to remote (D) or extremely improbable (E).

TABLE 1 HAZARD PROBABILITIES

| Descriptive Word | Level | Probability of Occurance |
|---|---|---|
| Frequent | A | Likely to occur frequently |
| Reasonably Probable | B | Will occur several times in life of an item |
| Occasional | C | Likely to occur sometime in life of an item |
| Remote | D | So unlikely, it can be assumed that this hazard will not be experienced |
| Extremely Improbable | E | Probability of occurance cannot be distinguished from zero |
| Impossible | F | Physically impossible to occur |

## SECTION 2

## MAJOR HAZARDS

The major hazards of the high current repetitive switch were evaluated by component. The major components which present hazards to personnel and equipment are the rotor, the brushes, the shaft and couplings, and the bus bars and cables. The hazards presented by these components, the severity of each hazard, the probability of occurrence of each hazard and the action taken to achieve acceptable levels of safety are tabulated in Table 2.

Table 2

Hazard Summary

| COMPONENT | HAZARD | SEVERITY | PROBABILITY | ACTION |
|---|---|---|---|---|
| ROTOR | DISINTEGRATION | II | E | DO NOT OPERATE OVER 3000 RPM. |
| ROTOR | INSULATOR LOSS/FRAGMENTATION | II | C | CONTAINMENT VESSEL DESIGNED TO CONTAIN DEBRIS. DO NOT OPERATE ABOVE 500 RPM WITHOUT VESSEL IN PLACE. |
| ROTOR | INSULATOR LOSS/UNBALANCED | III | C | SWITCH BOLTED DOWN TO FLOOR. |
| BRUSHES | BRUSH LOSS/DISINTEGRATION | II | C | DON'T OPERATE WITHOUT ROTOR CONTAINMENT IN PLACE. |
| SHAFTS/COUPLINGS | ENTANGLEMENT OF OPERATORS | II | D | PANELS PREVENT ACCESS TO ROTATING EQUIPMENT. DO NOT OPERATE WITHOUT PANELS ON SWITCH. |
| SHAFTS/COUPLINGS | COUPLING FAILURE/FRAGMENTATION | IV | D | PANELS WILL CONTAIN FRAGMENTS. |
| BUSBARS/CABLES | HIGH VOLTAGE SHOCK | II | D | LIMIT PERSONNEL ACCESS TO SWITCH SYSTEM DURING TESTING. ALWAYS SHUT OFF POWER SUPPLY AND CIRCUIT BREAKER BEFORE EXAMINING SWITCH OR COIL. ALWAYS CONNECT INSTRUMENTS WITH APPROPRIATE ISOLATION. |

The switch rotor turns at high speed, is relatively highly stressed and clearly presents a potential hazard. The worst hazard would result from disintegration of the rotor and subsequent launching of high velocity fragements into the room. At full design speed of 3000 rpm the stress in the rotor is well below the yield strength of the rotor material. The rotor is designed very conservatively from a mechanical point of view and, providing the design speed of the switch is not exceeded, this hazard is extremely improbable.

The insulating inserts in the switch rotor are bonded to the rotor. This bond could conceivably fail resulting in insulator loss and fragmentation. Insulator fragments could then be launched into the laboratory resulting in potentially severe damage. This hazard was anticipated during design of the switch and a containment vessel was placed around the rotor. The vessel is designed to contain any debris which might be launched during disintegration of an insulating insert. No high velocity fragments could escape from this vessel with adequate energy to do any significant damage in the laboratory. The switch should therefore not be operated above 600 rpm without this vessel in place.

The loss of an insulating insert will result in considerable rotor imbalance and subsequent high vibration levels. The operator can quickly shut the switch down. However, it is conceivable that the high vibration levels could cause the entire switch to move within the laboratory and perhaps tip over and injure personnel or damage equipment. This hazard was anticipated and the entire switch mechanism is firmly bolted to the floor with 1/2 inch bolts and anchors. Gross motion or tipping of the switch is therefore prevented.

Brushes could conceivably be mechanically torn from the brush strap or fragmented during switch operation. Brush fragments could then be launched into the room and would present a severe hazard. The containment vessel placed around the rotor is designed to contain this debris and prevent it from entering the room. The switch should therefore not be operated or the brushes actuated without this vessel in place.

The high speed rotating shafts and couplings which connect the drive motor to the rotor present a potentially severe hazard to operators. Clothing or tools could become entangled in the shafts resulting in severe injury and major system damage. Panels are installed on the switch which totally enclose the motor, shafts and couplings. When these panels are in place it is impossible for an operator to reach any of the rotating components within the switch. Therefore the switch should not be operated without these panels in place.

There are two couplings which connect the motor to the torque transducer and the torque transducer to the rotor shaft. These couplings are designed to accommodate slight misalignments of the shafts, to provide isolation between the various components and to protect the shafts and torque transducer from accidental torque excursions. These couplings may fail and fragment occasionally during operation. The resulting fragments could present a hazard to personnel and equipment. The panels provided on the switch should safely contain the resulting fragments and prevent any serious damage in the laboratory.

The cables and bus bars which bring current from the high current supply to the switch are bare of insulation in several places. In particular the terminals to the switch are exposed and can present a severe high voltage hazard to operators and equipment. A number of steps should be taken to limit the probability of occurrence of this hazard. Firstly, personnel access to the switching system should be limited with appropriate barriers and warning lights during operation of the switch. Secondly, the power supply should always be shut off and the main circuit breaker tripped before any close examination of the switch is undertaken. Finally, all instruments should be connected to the switch with adequate provision for isolation.

## SECTION 3

## CONCLUSION

All of the hazards identified in Table 2 have been adequately addressed either in the design of the switch system or in the operating procedures described. No hazard is anticipated which will injure or harm personnel or result in severe system damage. Some minor damage to switch components from component failure should be expected during the life of the device. These minor failures will not result in injury to personnel or damage to any auxiliary equipment. No catastrophic failure modes which would produce severe injury or damage are anticipated.